Electron-Cloud Build-up: Summary*

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Abstract

I present a summary of topics relevant to the electron-cloud build-up and dissipation that were presented at the International Workshop on Electron-Cloud Effects "ECLOUD'07" (Daegu, S. Korea, April 9-12, 2007). This summary is not meant to be a comprehensive review of the talks. Rather, I focus on those developments that I found, in my personal opinion, especially interesting. The contributions, all excellent, are posted in http://chep.knu.ac.kr/ecloud07/.

OBSERVATIONS

The electron cloud is observed at all machines where it has been looked for, although in some cases it may need to be triggered by tuning the beam or machine conditions to deliberately enhance the effect. A RFA electron detector has been installed in the FNAL Main Injector (FNAL-MI), which shows a clear electron signal at transition energy, when the bunch length is shortest. Evidence for an electron cloud also exists at the Tevatron (R. Zwaska). At CESR there is evidence for an effect from the electron cloud on the beam both for positron and electron beams (M. Palmer). Fairly detailed measurements with dedicated instrumentation have been carried out at the HCX heavy-ion facility, including a direct measurement of the electron cloud density (A. Molvik, M. Kireeff-Covo). Many new measuremnts were reported from KEKB (J. Flanagan, M. Tobiyama, K. I. Kanazawa, S. Kato, M. Nishiwaki, H. Jin, T. Ieiri; see below for further comments) and BEPC (Y. D. Liu). At the SNS there is no significant electron-cloud under nominal operating conditions, but dedicated experiments with unbunched beams and uncorrected chromaticity did show an electron-cloud signal according to expectations (S. Cousineau). At RHIC, the observed electron flux correlates well with pressure rise, which is due mostly to gas desorption upon electron-wall impact (W. Fischer, S. Y. Zhang). In tests conducted with zero magnetic field at the ANKA superconducting undulator, electrons are suspected but not conclusively implicated in the measured heat load (S. Casalbuoni). At the PSR, the "swept" electron signal decay constant is $\sim 60-90$ μs. The suspicion is that there is a significant source of primary electrons from beam scraping in the quadrupole magnets, and then these electrons move into the neighboring field-free regions owing to the $\mathbf{E}\times\mathbf{B}$ drift (R. Macek, Y. Sato).

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SECONDARY ELECTRON EMISSION

The electron cloud is a local issue: the chamber geometric and electronic properties are important factors affecting the electron density. The seed, or primary, electrons may be important, and their intensity may have strong local fluctuations. The effects of the electron cloud on the beam (instabilities, emittance growth) is a global issue, as these effects depend on an integral of the beam traversal through the machine, typically for many turns. In most (but not all) cases, the electron cloud build-up is dominated by the secondary emission yield (SEY) $\delta(E_0)$ of the chamber wall, where E_0 is the incident electron energy. If the effective SEY $\delta_{\rm eff}$ (ie., the SEY averaged over electron-wall collision events over a given time interval) is > 1, there is a strong nonlinear amplification of the electron density in time until a saturation is reached owing to the space-charge forces. The saturation level is typically comparable with the beam neutralization level.

Significant progress in measuring and understanding the SEY and its conditioning was reported by the KEKB group (S. Kato, M. Nishiwaki), using an in-situ setup. Various material samples were bombarded with $E_0 = 5$ keV electrons, their SEY measured in situ without breaking vacuum, and their surface structure analyzed with the x-ray photoemission spectrum (XPS) technique. An electron energy $E_0 = 500$ eV was also used to bombard the samples. In all cases analyzed (copper, aluminum, stainless steel) it was observed that the peak SEY $\delta_{\rm max}$ was reduced down to ~ 1 after a dose in the range $\sim 0.01-1$ C/cm^2. Conditioning of the surface samples due to the electron cloud plus synchrotron radiation in the KEKB beam chamber was also observed, showing $\delta_{\rm max} \gtrsim 1$. The XPS analysis showed that, in the case of electron-gun bombardment at $E_0 = 5$ keV, the surface exhibited graphitization, which is presumably the reason why $\delta_{\rm max}$ reached such a low value. Graphitization was not seen in samples exposed to synchrotron radiation from the beam. It seems desirable to repeat the measurements at $E_0 = 100$ eV, since this is a more typical range for the electron-cloud energy. Also, the suggestion was expressed to do the measurement on SS316LN stainless steel samples, not just SS304.

A few SEY issues that have been raised in the past [1] were not addressed at this workshop, and remain to be clarified: (1) It would be desirable to measure the secondary emission energy spectrum at various incident electron energies E_0 in the range $E_0 = 10-1000$ eV and disentangle the three main components, namely true secondaries, rediffused and backscattered electrons [2]. This is generally a challenging task because the measurement of the spectrum itself conditions the surface. (2) Quantify how the above-mentioned three components condition with electron bombardment dose (probably not at the same rate). An important practical issue is to know the fraction of rediffused electrons as a function of E_0, because these electrons can contribute significantly to the electron-cloud density build-up owing to their broad emission spectrum [3]. (3) Detailed studies of the low-energy region ($E_0 < 20$ eV) of $\delta(E_0)$, because this region controls the dissipation rate of the electron cloud in between successive bunches, or following beam extraction: the higher $\delta(0)$, the longer the electrons survive [4, 5].

MITIGATION

Various ways to reduce secondary electron emission were described. One novel way is to engrave millimiter - scale grooves on the chamber surface (M. Pivi) running parallel to the beam direction. The grooves suppress $\delta_{\rm eff}$ by effectively increasing the surface roughness, which traps the secondary electrons. Although recent preliminary tests at PEP-II were inconclusive owing to unexpected confusion from primary electrons emitted by the synchrotron radiation, there is general agreement that such grooved surfaces will be effective in reducing $\delta_{\rm eff}$. Clearing electrodes were also discussed as possible electron-cloud suppressors for the ILC damping ring. A new concept for clearing electrodes, consisting of thin metallic stripes etched on an enamel substrate, which is itself coated on the vacuum chamber surface, was presented (W. Fischer, summary of ECL2 workshop). While, in general, there is high confidence, in principle, in the effectiveness of clearing electrodes, the actual implementation raises concerns such as: What is the operational reliability, durability and impedance of the electrodes? What is the fraction of the circumference they can realistically cover? In the case of the metal-on-enamel electrodes, what is the percentage of enamel exposed to the vacuum, and what is its SEY? Would the enamel charge up?

SIMULATIONS AND BENCHMARKS

Effort continues on the simulation of the build-up of the electron cloud for various machines, with recent focus on the ILC damping rings (ILC-DRs) (M. Pivi, C. Celata) and the proposed Test Accelerator at CESR (CESR-TA) (M. Palmer), which will include dedicated wiggler sections mimicking what is expected at the ILC-DRs. Preliminary three-dimensional simulations for the wigglers were reported (C. Celata), with self-consistent simulations to come later, in stages of increasing complexity. Simulations for the FNAL-MI (M. Furman) combined with the above-mentioned measurements of the electron flux with the RFA (R. Zwaska) allow one to infer $\delta_{\rm max} = 1.4-1.5$. However, direct measurements of MI vacuum chamber samples carried out at SLAC show $\delta_{\rm max} = 2$, a significant discrepancy with the inferred value. It appears, however, that the samples were exposed to air after removal from the MI vacuum chamber and before being measured at SLAC; this would explain the large measured value of $\delta_{\rm max}$. It seems important, therefore, to measure the SEY in situ whenever possible.

Fully self-consistent simulations (FSCS) remain a challenge, as they bring in large disparities in the time scales, possibly large length scales, and a possible mixture of the "s" and "t" descriptions of the time development of the beam. Progress was reported within the ORBIT code, as applied to the SNS (S. Cousineau).

Renewed hope for significantly faster FSCS has recently arisen owing to a new algorithm (J.-L. Vay), in which the computation is done in a Lorentz-boosted frame of reference. By judiciously choosing the relativistic γ-factor of the boosted frame somewhere in between 1 and the beam γ, it is possible to match the time and length scales of the beam and the electron cloud, thereby alleviating or eliminating the problem of large time scale disparities. A test case shows a speed-up of ~ 3 orders of magnitude relative to the calculation in the Lab frame with virtually identical results for the beam size evolution. This algorithm makes the FSCS as fast as the "quasi-static approximation" algorithm. Issues arising from the shifted simultaneity of events, and translating the beam phase space from the boosted frame to/from the Lab frame remain to be clarified.

COMMENTS

The above-mentioned new in-situ measurements of the SEY at KEK (S. Kato, M. Nishiwaki) indicate that full conditioning of the SEY (ie., $\delta_{\rm max} \simeq 1$) is readily achieved by electron bombardment. If so, one might ask why the electron cloud remains an operational problem in many machines? I don't think that primary electrons, mainly photoelectrons, are produced in sufficient numbers to explain a significant electron cloud effect, except in the KEKB positron ring and, possibly, in parts of the straight sections in PEP-II. In hadron machines, the puzzle is magnified by the absence of photoelectrons and the practically insignificant source of other primary electrons. Here are some speculations on how one might reconcile $\delta_{\rm max} \simeq 1$ with a significant electron-cloud effect:

1. Lots of electrons accumulate in the magnetic field of the quadrupole magnets and dissipate very slowly due to the magnetic bottle effect. Evidence for this accumulation exists at KEKB, PSR and possibly the SPS.

2. $\delta_{\rm max}$ could be smaller ($\simeq 1$) than typically assumed while $\delta(0)$ is larger than typically assumed ($\delta(0)$ also $\simeq 1$).

3. Hadron storage rings are not as well conditioned as positron storage rings because the average electron-wall impact energy E_0 is typically lower in the former than in the latter.

4. Something else.

None of these speculations seems compelling (except possibly for Item 4!). Rough quantitative evaluations are needed before significant effort is invested in them. Item 2 is based on the premise that either $\delta_{\max}$ or $\delta(0)$ drive the electron cloud density build-up when the other is kept fixed; there are simple reasons and good simulated evidence for this [4], and there are measurements that show that $\delta(E_0)$ has an upturn as $E_0 \to 0$ [5]. A possible problem with this speculation is that the PSR swept-electron signal in field-free regions seems to imply $\delta(E_0) \simeq 0.5$ at low values of E_0 [6]. On the other hand, this does not necessarily contradict $\delta(0) \simeq 1$. Item 3 is in turn based on the assumption that low-energy electron-wall collisions condition the surface less effectively than higher-energy collisions. It seems desirable, therefore, to verify or disprove this assumption by repeating the KEKB measurements with an electron gun at, say, $E_0 = 100$ eV.

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